Contract # N00014-14-C-0020

Pilot-in-the-Loop CFD Method Development

Progress Report (CDRL A001)

Progress Report for Period: July 21, 2016 to October 20, 2016

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Section I: Project Summary

1.   Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) virtual dynamic interface (VDI) research topic area "Fast, high-fidelity physics-based simulation of coupled aerodynamics of moving ship and maneuvering rotorcraft".   The work is a collaborative effort between Penn State, NAVAIR, and Combustion Research and Flow Technology (CRAFT Tech). This document presents progress at Penn State University.

All software supporting piloted simulations must run at real time speeds or faster. This requirement drives the number of equations that can be solved and in turn the fidelity of supporting physics based models. For real-time aircraft simulations, all aerodynamic related information for both the aircraft and the environment are incorporated into the simulation by way of lookup tables. This approach decouples the aerodynamics of the aircraft from the rest of its external environment. For example, ship airwake are calculated using CFD solutions without the presence of the helicopter main rotor. The gusts from the turbulent ship airwake are then re-played into the aircraft aerodynamic model via look-up tables. For up and away simulations, this approach works well. However, when an aircraft is flying very close to another body (i.e. a ship superstructure) significant aerodynamic coupling can exist. The main rotor of the helicopter distorts the flow around the ship possibly resulting significant differences in the disturbance on the helicopter. In such cases it is necessary to perform simultaneous calculations of both the Navier-Stokes equations and the aircraft equations of motion in order to achieve a high level of fidelity. This project will explore novel numerical modeling and computer hardware approaches with the goal of real time, fully coupled CFD for virtual dynamic interface modeling & simulation.

Penn State is supporting the project through integration of their GENHEL-PSU simulation model of a utility helicopter with CRAFT Tech's flow solvers. Penn State will provide their piloted simulation facility (the VLRCOE rotorcraft simulator) for preliminary demonstrations of pilot-in-the-loop simulations. Finally, Penn State will provide support for a final demonstration of the methods on the NAVAIR Manned Flight Simulator.

Activities this period
During this report period, the steady state trim characteristics of GENHEL-PSU coupled with a CFD solver is compared with the standalone GENHEL-PSU and the USAAEFA test data contained in Ref. 1 to ensure the developed model behaves properly in forward flight regimes. Initial results have been presented for a hover case and airspeeds up to 100 knots. Coupled GENHEL-PSU and CFD solver simulations produced a good correlation with the flight data.

GENHEL-PSU/CFD Coupling Interface
The coupling between GENHEL-PSU and the CRUNCH CFD® solver has been developed [2] and used for a variety of flight scenarios in the scope of this project [3, 4]. During this report period, a validation study has been performed to determine the steady state trim characteristics of this developed tool and ensure the model behaves properly in forward flight regimes. These regimes are important for the ship approach simulations because these simulations usually require a series of low-speed forward flight maneuvers. Therefore, we would like to investigate the steady-state characteristics of the model to satisfy the project requirements.

In fully coupled solutions, Navier-Stokes CFD is used to calculate the flow field induced by the main rotor (at present we do not calculate the flow induced by the tail rotor, although this implementation has been recently completed and simulation results will be presented on the next reporting period). The rotor downwash impinges on the airframe as well as the ground and other objects in the environment. In turn, this flowfield affects the local aerodynamics of the main rotor blade sections, affecting blade air loads, and thus affects the induced flow. All of these interactions are inherently coupled. In fully coupled simulations, the CFD solver models the inflow, ground effect, and impingement of main rotor wake on the fuselage and empennage. Therefore, the corresponding modules in GENHEL-PSU (Pitt-Peters inflow model, empirical models of ground effect and rotor / airframe interactions) are disabled when running in fully coupled mode, so as to not "double count" these effects.

In fully coupled simulations, the main rotor blade element forces are used to insert source terms in the Navier- Stokes momentum equations solved in CFD. A series of coordinate system transformations are used to calculate the force vector and its location within the CFD domain, and the source terms impart momentum on the flow solution to generate rotor downwash. The flow velocities at the main rotor blade elements, and at the aero center locations for the fuselage, tail rotor, horizontal stabilizer, and vertical stabilizer (Figure 1) are fed back to the flight simulation model. At present, we account for rotor downwash influence on the fuselage and empennage, but these airframe components do not influence the CFD flow solution. Normally, in a rotorcraft simulation, local flow velocities are calculated at aerodynamic control points at various points of the airframe. The local flow velocities are based on the superposition of free stream flow, angular motion of the aircraft, and an empirical correction due to main rotor wake impingement. The local flow velocity vector at the control points are used to compute dynamic pressure and aerodynamic angles, which are used in table look-ups of aerodynamic force coefficients. Currently, in the coupled simulations, the rotor downwash computed by CFD "flows through" the airframe. We then use the CFD flow velocities at the aerodynamic control points for the wake impingement correction (in place of the empirical model). Distortion of the flow due to airframe could be modeled with overset or moving grids, but that would be very expensive. In the future, we hope to add the blockage effects of the fuselage in a computationally efficient way, but this is a matter of ongoing research. While the current approach has obvious limitations, it is substantially more accurate than current modeling methods for wake impingement that relies on crude empirical correction factors.
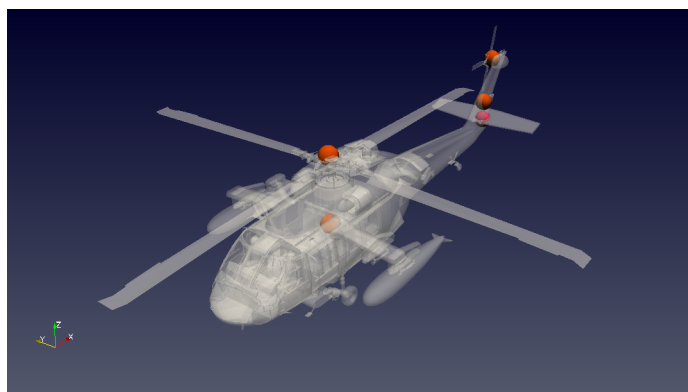

Figure 1 – Source term points located on the helicopter body used for the rotor inference calculations

Level Flight Trim Simulations

In the scope of this report period, the level-flight trim simulations have been performed using GENHEL-PSU coupled with CRUNCH CFD solver for different airspeeds; and the results were compared with the USAAEFA test data and the standalone GENHEL-PSU model.

Level-flight trims were determined for airspeeds from 0 to 100 knots in 20-knots increments. 90 seconds of free-flight coupled simulations were performed for 6 different airspeeds. Initial trim states were obtained using Pitt-Peters inflow model and then helicopter entered to free fly-mode when the simulation starts. During the coupled simulations, on every time step, the GENHEL-PSU sends the blade aero loads and positions to the CFD solver and the CFD solver returns back the local flow velocities. Then, GENHEL-PSU helicopter re-trims itself to a new trim state. The aircraft configuration was set-up to duplicate static-trim cases performed by Sikorsky to match USAAEFA test data. Flight values of aircraft weight, c.g. location, and constant main rotor speed (27 rad/sec) were used (**Table 1**). The simulations performed at 5250 ft. density altitude. Not to 'double count' the aerodynamics effects on the rotor blade, the corrections factor terms defined in GENHEL-PSU rotor module were removed. A non-linear dynamic inversion controller were used to hold the helicopter at a fixed position in the air. The control stick positions, aircraft attitudes and main rotor required power are presented as result.

Table 1 – Modifications on aircraft configuration.

Gross Weight	16000 lb
C.G. Station	351.0 in.
C.G. Waterline	231.5 in.
Density Altitude	5150 ft.

In the CFD simulations, a 300ft. x 300ft. x 300ft. computational domain with a refined mesh resolution region around the rotor disk was used for the hover case (**Figure 2**). Inflow/outflow boundary is applied to the side and top surfaces of the domain; and outflow is applied to the bottom surface. Coupled simulations have been performed for 90 seconds. For the forward flight cases, the same computational domain was expanded along with the +X axis since the downwash is expected to be skewed along the downstream. The refined mesh resolution region has also been tailored to cover the skewed rotor downwash (**Figure 2**). In forward flight cases, inflow and outflow boundaries were applied to the surfaces in the upstream and downstream direction, respectively. A slip-wall boundary is applied to the rest of the domain surfaces.
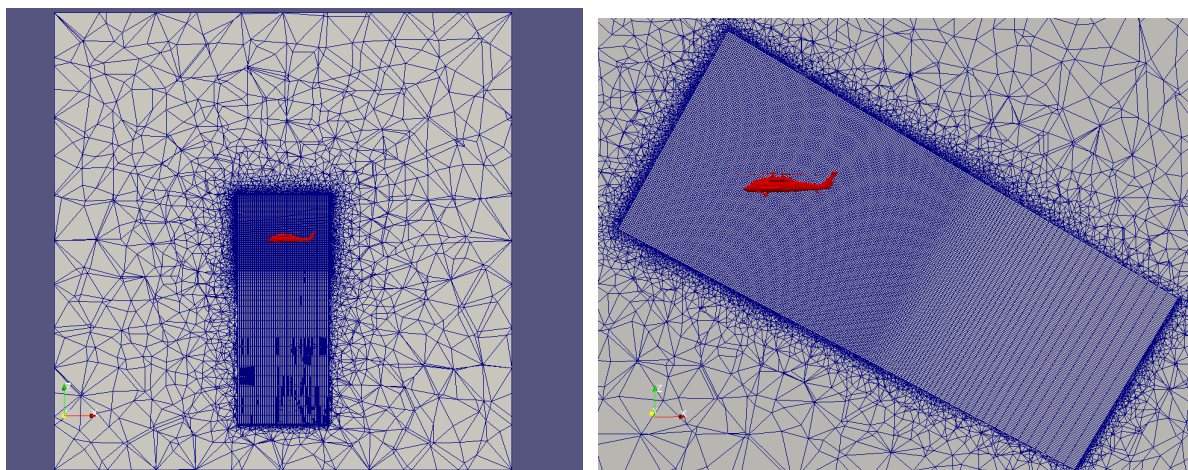

Figure 2 – Computational domain used in the CFD simulations: hover (left), forward flight (right).

Figure 3 and Figure 4 show the rotor induced velocity distributions for the hover and 20 knots forward flight cases, respectively. As it can be seen, the downwash is perfectly developed in both cases. Tip vortex and swirl generated by the blade rotation is successfully modeled in the simulations.
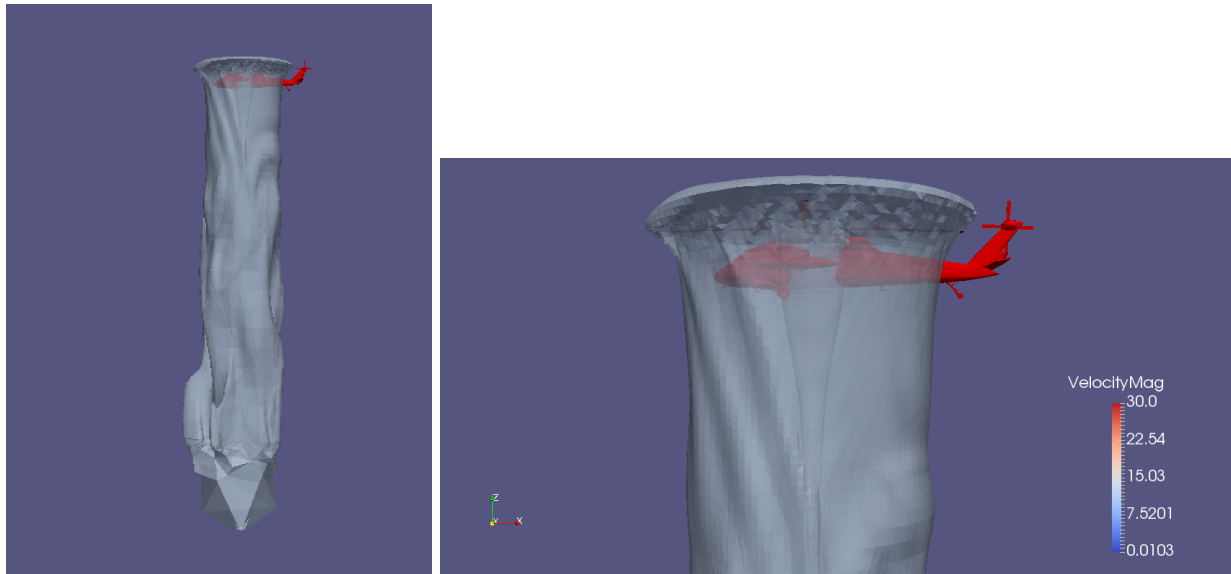

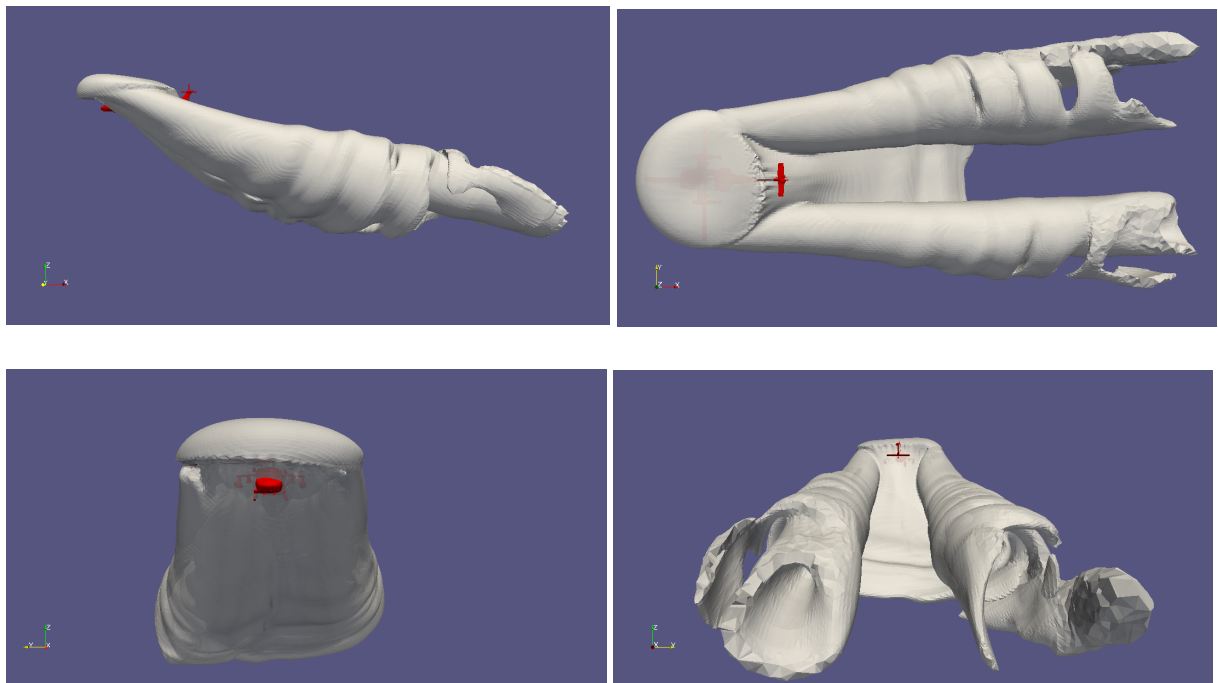**Figure 3 – Velocity magnitude iso-volume for the hover case**

Figure 4 – Velocity magnitude iso-volume for 20 knots forward flight case.

Figure 5 to **Figure 7** show the comparisons for level-flight trims obtained using the coupled GENHEL-PSU and CRUCNH CFD solver simulation, standalone GENHEL-PSU and USAAESA test data [Ref. 1].

The agreement between the standalone GENHEL-PSU and the flight data is very good for almost all speeds except for a nearly constant pedal bias of approximately 0.5 in. to the right. Also, there is less agreement at lower speeds. Previously, a very similar behavior has been shown for the different versions of GENHEL in Reference 1. In the same study, all these discrepancies were explained as result of the pilot's difficulty in achieving trimmed flight on the back side of the power-required curve and the simplified modeling of the impingement of the main rotor downwash on the fuselage and stabilator (Ref. 1).
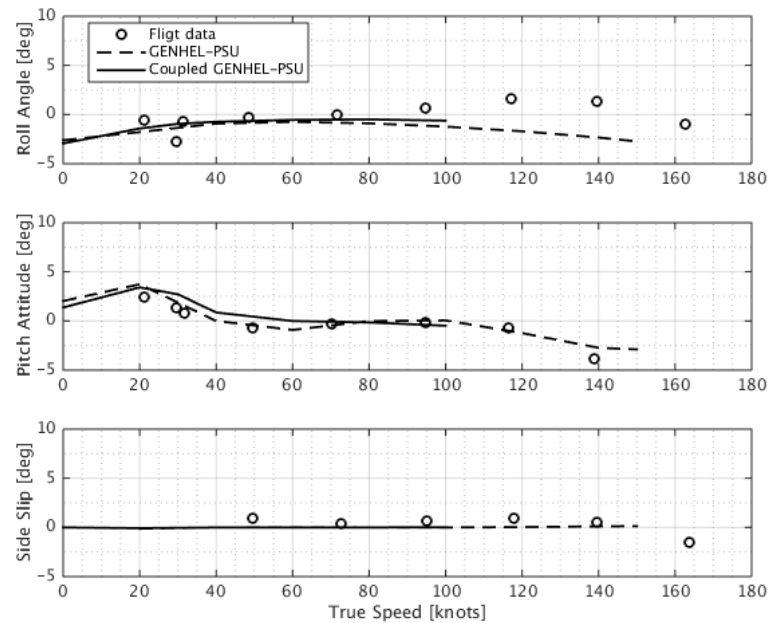
Figure 5 – UH-60 Black Hawk level-flight static trim, attitudes.
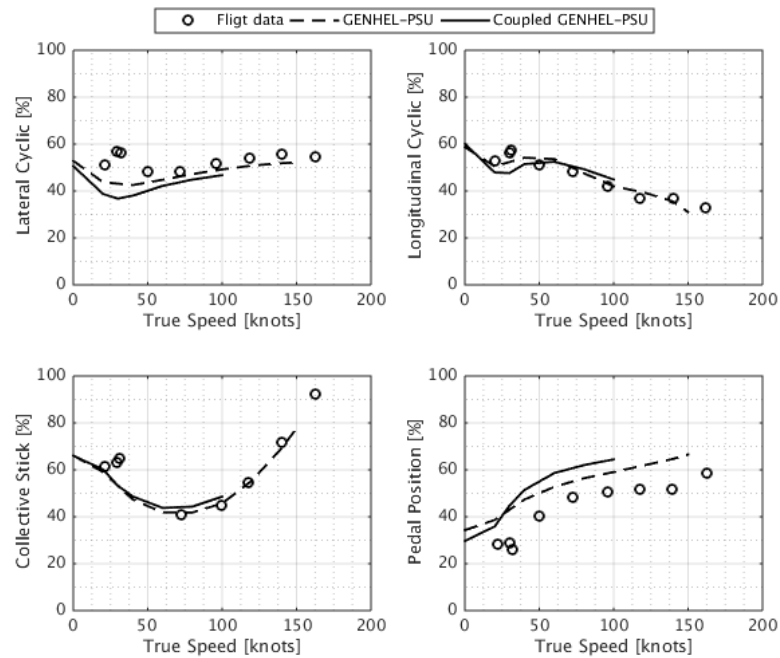
Figure 6 – UH-60 Black Hawk level-flight static trim, control stick positions.

As mention before, GENHEL-PSU uses a simplified analytical model (Pitt-Peters) for wake impingement calculations that relies on crude empirical correction factors. All the correction factors are mostly implemented on to match the simulation results with the flight data. In fully coupled simulations, we took out all these correction factors, since we replace this simplified wake impingement model with a more accurate Navier Stoke's calculations. As you can see, the agreement between the coupled GENHEL-PSU and the flight data is as good as the standalone GENHEL-PSU except this time, there is a constant pedal offset to left (Figure 6). There is still a less agreement at lower speeds. The power-required curve is slightly better in the coupled simulations (Figure 7). The difference between the simulation and test data at lower speed got worse when the simulation is coupled. However general trend is very similar on both simulation as well as the test data.
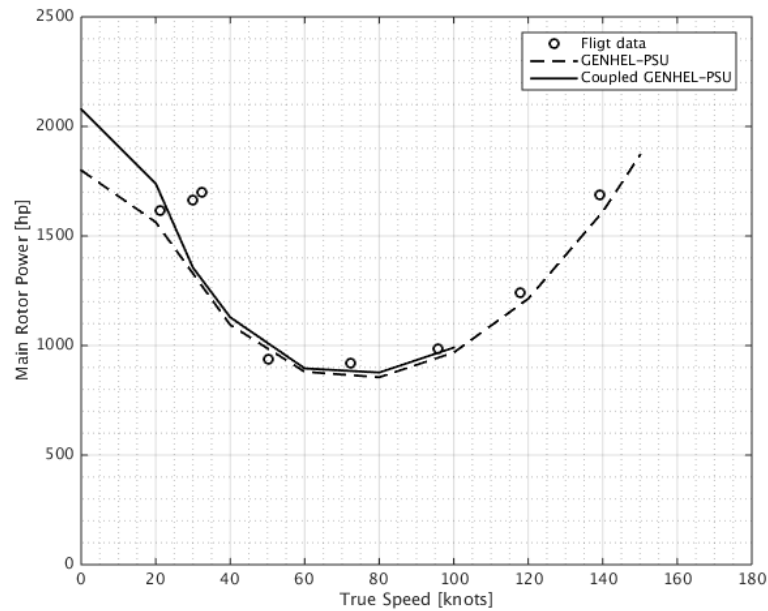

Figure 7 - UH-60 Black Hawk level-flight static trim, main rotor required power.

2.   **Significance of Results**

The steady state trim characteristics of the GENHEL-PSU coupled with CRUCNH CFD solver are compared with the standalone GENHEL-PSU and USAAEFA test data contained in Ref. 1. Results have been presented for airspeeds up to 100 knots and a hover case. Coupled GENHEL-PSU simulations have been performed without the correction factors defined in GENHEL code to show the actual impact of coupling effects. The agreement between the coupled GENHEL-PSU simulations w/o the correction factors and the test data is as good as the one between the standalone GENHEL-PSU with the correction factors and test data. However, there is a significant difference at the pedal predictions and we will be investigating this in the scope of next report period.

Results give us a confidence on the developed tool, and show us a promising performance towards using this tool for different flight scenarios.

3.   **Plans and upcoming events for next reporting period**

•   We are planning to improve the current implementation of CFD flow velocities in the rotor interference module. Currently, we are probing the flow field from a single point source point the fuselage, tail rotor, horizontal stabilizer, and vertical stabilizer. This results in sudden changes on the rotor interference

velocities, especially when the helicopter moves along the grid cells. This problem can be easily solved by using a line source, instead of using a single point source, to probe the flow field at the aero these centers. We are hoping finish this implementation before the end of next reporting period.

- We have finished the implementation of tail rotor to the coupling interface and recently started performing initial tests using this new improved coupling interface. Simulation results including this new tail rotor implementation will be presented in the scope of next quarterly progress report.

- The collaboration between Penn State and CRAFT Tech is still continuing. We are working on implementing the GPU technology to the coupling interface code. CRAFT Tech will implement OpenACC directives to their structured CFD solver, CRAFT CFD. There is a plan to test this new more efficient solver at Penn State clusters with the GPU acceleration support. We hope to get a sufficient speedup in the solver performance of the CFD computations so that a ship airwake model on the order of 5-10 million grid cells can included in the fully coupled simulation framework.

4.   References

[1] Ballin, Mark G. "Validation of a Real-Time Engineering Simulation of the UH-60A Helicopter" Ames Research Center, CA, 1987.

[2] Oruc, I., Horn, J.F., Polsky, S., Shipman, J. and Erwin, J., "Coupled Flight Dynamics and CFD Simulations of the Helicopter/Ship Dynamic Interface", American Helicopter Society Forum 71, Virginia Beach, VA, May 2015.

[3] Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., "Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions," AIAA Modeling and Simulation Technologies Conference, AIAA SciTech, San Diego, CA, January 2016.

[4] Oruc, I., Shenoy, R., Shipman, J., and Horn, J.F., "Toward Real-time Fully Coupled Flight Simulations of the Helicopter/Ship Dynamic Interface," American Helicopter Society Forum 72, West Palm Beach, FL, May 2016.

5.   Transitions/Impact

No major transition activities during the reporting period.

6.   Collaborations

We had several tele-conference meetings with CRAFT Tech during this reporting period. We have discussed the potential efficiency improvement on the coupling interface.

The work continues to involve close collaboration between PSU, CRAFT-Tech, and NAVAIR.

7.   Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Ilker Oruc, PhD Student

8.   Publications

Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., "Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions," AIAA Journal of Aircraft. (This journal paper is currently in the revision process. We were asked to clarify a coupled of simulation results. We are hoping to submit the final version by the end of the year.)

Oruc, I., Shenoy, R., Shipman, J., and Horn, J.F., "Toward Real-time Fully Coupled Flight Simulations of the Helicopter/Ship Dynamic Interface," American Helicopter Society Forum 72, West Palm Beach, FL, May 2016.

Oruc, I., Horn, J.F., Shipman, J., and Shenoy, R., "Coupled Flight Dynamics and CFD Simulations of the Rotorcraft/Terrain Interactions," AIAA Modeling and Simulation Technologies Conference, AIAA SciTech, San Diego, CA, January 2016.

Oruc, I., Horn, J.F., Polsky, S., Shipman, J. and Erwin, J., "Coupled Flight Dynamics and CFD Simulations of the Helicopter/Ship Dynamic Interface", American Helicopter Society Forum 71, Virginia Beach, VA, May 2015.

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10.   **Acknowledgement/Disclaimer**